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Flow Rate of African Breadfruit Seeds Through Horizontal Orifices

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Abstract

The flow rates of African breadfruit seeds through circular and square horizontal orifices were measured at the moisture content of 8.25% w.b. with hoppers of 70° side slope from the horizontal. The equivalent diameters of the orifices ranged from 3.44 to 7.05cm for circular and square hoppers, while the hydraulic diameters were 4.47 to 8.05cm for both orifices. The data for the volume flow rates through the orifices fitted well the Beverloo law and increased as the orifice diameters increased. The exponents of the equivalent diameter in the power equation were 2.529 for the circular orifice and 2.568 for the square orifice, while those of the hydraulic diameter were 3.069 and 3.149 for circular and square orifices respectively. Also, the volume flow rate of the African breadfruit seeds decreased as the seed size increased from 0.66 to 0.82cm, and had high coefficient of determination (R^2) for both linear and power regression equations.

Keywords: Flow rate, African breadfruit seeds, horizontal orifices, orifice equivalent diameter, seed size.

1.0 Introduction

Several researchers (Chang and Converse, 1988; Moysey *et al.,* 1985; Chang *et al.,* 1984.; Beverloo *et al.,* 1961) have estimated the flow rate of grains through horizontal openings of bins, hoppers or grain handling systems for the purpose of properly sizing the openings in order to control grain flow to and from them. They found that volume flow rate depends on the material (mainly particle size and shape) and its moisture content and the hydraulic diameter of the opening. Others used the effective hydraulic diameter which is the reduction of the hydraulic diameter by the "empty annulus" whose width is 1.3 to 1.5 times the mean particle diameter. This "empty annulus" is important when the orifice dimensions are less than 20 times particle diameter (Wilcke *et al.,* 1992). Also, the flow rate may be affected by hopper slope when the slope is above 60° from the horizontal (William, 1977).

Some of these works have indicated that grain flow was proportional to between 2.5 and 3.0 power of the diameter of the opening. However, based on dimensional analysis, Berveloo *et al.* (1961) suggested that the flow rate of granular material was proportional to the diameter of the orifice raised to the 2.5 power and proposed a general equation (equation 1) for calculating the volume flow rate through various shaped orifices;

$$Q = 0.75 A_e g^{0.5} D_e^{0.5} \qquad \ldots 1$$

where Q = volume flow rate (m³/s), g = acceleration due to gravity (m/s²); $D_e = D_h - 1.4d$ D_e = effective orifice diameter (m); D_h = orifice hydraulic diameter (m); d = average size of grains (m); A_e = effective orifice area calculated from D_e (m²)

Based on the works of some of the above several researchers working with various grains and seeds, the American Society of Agricultural and Biological Engineers (ASABE) developed a Standard for the flow of grain and seeds through orifices (ASABE D274.1 FEB 2003) in which the equation for predicting flow rate was given as equation 2.

$$Q = C_o A D^n \qquad \ldots 2$$

where Q = volume flow rate (m³/h), A = area of orifice (cm²), D = hydraulic diameter of orifice (cm), C_o = coefficient (m³/cm$^{(n+2)}$h), n = exponent with value between 0.5 and 1.0.

The ASAE Standard stated that equation 2 has been validated for square and circular orifices in both horizontal and vertical orientations as well as for rectangular orifices of aspect ratios from 1.33 to

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2.67 in the horizontal orientation (Chang *et al.,* 1991). Also the orifice hydraulic diameters tested ranged from 7 to 30cm for different seeds and grains of moisture contents ranging from 4 to 22% w.b. Chang *et al.* (1984) and Chang and Converse (1988) in their work with wheat and sorghum found that the log-log scale plots of volume flow rate versus orifice diameter or side length were nearly linear for all tests, and proposed Equation 3 to be used to express flow rate.

$$Q = \alpha D^n \qquad \ldots 3$$

Where Q = volume flow rate (m^3/h), D = orifice size (diameter or side length) (cm), α and n = coefficients

Equation 3 will be used to express the volume flow rates of African breadfruit seeds in this paper. Volume flow rate was chosen to be the parameter expressed as a function of orifice size and other parameters instead of mass flow rate, because an orifice has direct effect or control over volume flow rate rather than mass flow rate. The grains and seeds tested in Literature include corn, wheat, sorghum, rape seed (canola), flaxseed, blackeyed peas and cotton seed. The flow rate of such seeds as African breadfruit seeds has not been reported in Literature.

2.0 Materials and Method

The circular and square holding bins with diameter/ side length 16.3cm and height 5cm has a 10cm deep hopper bottom sloping toward the central opening at an angle of 70^o from the horizontal, terminating with an orifice or opening 9.0cm (Figure 1). A 2cm vertical section of diameter/side length 9.0cm with a slide gate was attached to the orifice opening. Test circular and square orifices of hydraulic diameters/ side lengths 4.47, 5.05, 6.18, 7.14 and 8.05cm were constructed.

Twenty (20) kg of African breadfruit seeds were purchased from the local market at Owerri and thoroughly cleaned of debris, immature and shriveled seeds. Some of the seeds were used to fill 1000ml glass cylinder and then the bulk weight determined using an electronic weighing balance. This was replicated five times and the average taken to calculate the bulk density. Some seeds were also weighed and put in five test cups which were placed in an oven set at 103^{o}C for 24 hours and used to

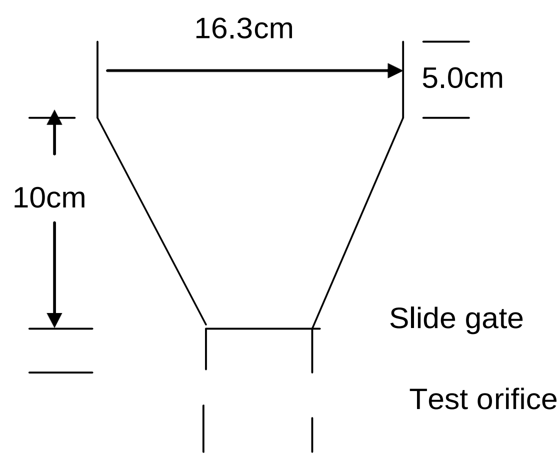

Figure 1: The test hopper configuration

determine the bulk seed moisture content gravimetrically. The remaining seeds (19.3kg) were classified into five seed size groups by sieve analysis according to their equivalent diameters. The size groups were 0.66, 0.70, 0.74, 0.78 and 0.82cm respectively with the groups having 1.6, 5.8, 6.0, 5.2 and 0.7kg weight of seeds respectively.

To start each test, the given test orifice is installed and the slide gate above it is closed. Some seed in each size group is poured into the hopper to fill it up to the brim. The sliding gate was opened to permit seeds to flow through the test orifice to a receiving bin and the time required for the holding bin to empty was measured with a stop watch (Figure 2). The bulk weight of the seeds was measured and the mass flow rate of the seeds was determined by dividing the seeds weight by the flowing time, while the volume flow rate was obtained from the values of the mass flow rate and the bulk density. For each D_h and d the test was repeated five times to check variability which ranged within $\pm$4% within each lot for square and $\pm$ 2.5% for circular orifices. A total of 125 reading were obtained and thereafter A_h, D_e, A_e, D_h/d were calculated and related to their respective volume flow rates.

3.0 Results and Discussion

The bulk density of the African breadfruit seeds used in this work was found to be 570 $\pm$ 97kg/m^3 while the moisture content was 8.25 $\pm$ 0.38% w.b. The distribution of the seed sizes is given in Table 1 which shows that over 88% of the seeds fall within the size

Figure 2: Actual flow rate measurement with square hopper.

range of between 7.0 and 7.8mm. For the five flow rate tests conducted for each orifice size and seed size, the results were statistically similar for the replicated tests with standard error of a treatment mean between 0.025 to 0.056 m^3/h for circular orifices and 0.049 to 0.077 m^3/h for square orifices. The experimental data obtained were analyzed into power regression equations (as in equation 3) and linear regression equations and their coefficients given in Table 2 with their R^2.

3.1 Effect of Seed Size (d)

As the seed size increased, the flow rate decreased. The R^2 was higher for linear than power regression for both circular and square orifices. Also flow rate was higher (Q_c) through circular orifice than (Q_s) through square orifice by about 30%, probably because the area making up the edge of the square corners was not effectively used by the African breadfruit seeds (Chang *et al*, 1984).

The effect of particle diameter on flow rate of grains has been implicated in the "empty annulus" phenomenon which reduces the orifice hydraulic diameter to the effective or equivalent orifice diameter. The width of the "empty annulus" is 1.3 to 1.5 times the mean particle diameter and it is important when orifice dimensions are less than 20 times particle diameter (Wilcke *et al.,* 1992).

3.2 Effects of Hydraulic and Effective Orifice (D_h and D_e).

Most researchers (Beverloo *et al.,* 1961; Brown and Richards, 1970; Chang *et al.,* 1984, 1990; Moysey *et al.,* 1985) have found volume flow rate to depend on orifice diameter (hydraulic or effective). Also, they found volume flow rate versus orifice diameter to have power regression relationship as in Equation 3. Table 2 shows that the power relationships have higher R^2 than the linear relationships.

Table 1: African breadfruit seeds distribution size

Seed Size (cm)	0.66	0.70	0.74	0.78	0.82
Bulk Mass (kg)	1.6	5.8	6.0	5.2	0.7
% of Total	8.24	30.05	31.09	26.94	3.63

Table 2: Coefficients of linear and power regression equations of data for the flow rate of African breadfruit seeds coefficients

	circular			Square		
Linear	a	b	R^2	a	b	R^2
Particle size	9.035	-0.305	0.999	6.624	-0.247	0.999
D_h/d	4.529	0.205	0.996	2.973	0.187	0.996
D_h	-6.919	1.758	0.980	-5.122	1.439	0.975
D_e	-5.098	1.758	0.980	-3.748	1.473	0.967
A_h	-1.869	0.185	0.994	-1.347	0.131	0.993
A_e	-0.865	0.216	0.998	-0.718s	0.167	0.990
Power	α	n	R^2	α	n	R^2
Particle size	13.16	-0.330	0.998	10.24	-0.380	0.998
D_h/d	3.058	0.332	0.998	2.018	0.381	0.998
D_h	0.012	3.069	0.999	0.011	3.149	0.999
D_e	0.055	2.529	0.999	0.053	2.568	0.999
A_h	0.016	1.571	0.998	0.011	1.574	0.999
A_e	0.075	1.264	0.999	0.053	1.284	0.998

With D_h the exponent was 3.069 for circular and 3.149 for square orifices which are slightly higher than the 3.0 found in Literature (Fowler and Glastonbury, 1959; Brown and Richards, 1960). This may be because of the near spherical shape of African breadfruit seeds. However, using D_e, the exponent was 2.529 for circular and 2.568 for square horizontal orifices which are within the range 2.5 to 3.0 found in Literature (Chang *et al.,* 1984; Chang and Converse, 1988; Kusiñska and Olejarczyk. 2005). Thus, for African breadfruit seeds, D_e could be used instead of D_h to correlate its volume flow rate.

3.3 Effect of Hydraulic and Effective Orifice Area (A_h and A_e)

Orifice area also plays an important role in volume flow rate of granular materials and for African breadfruit seeds volume flow rate was higher through circular orifice than square orifice as observed by Chang *et al.* (1984) for corn. However, the difference is about 30% as observed in d above, due may be to the size and shape of the African breadfruit seeds.

In Table 2, it is only the exponents of A_e that are exactly half that of D_e, thereby confirming using the equivalent hydraulic orifice dimensions to correlate volume flow rate of African breadfruit seeds.

3.4 Effect of Ratio of Orifice Diameter to Particle Diameter ($D=D_h/d$)

This ratio (D) has been found to be critical to free flow of granular materials (Kvapil, 1965; Brown and Richards, 1970). Recent studies show that this ratio influences jamming of granular matter (Nedderman *et al.,* 1982; Garcimartin, 2007). Also, Zuriguel *et al.* (2003) and Mankoc *et al.* (2007) have found flow rate of grains through orifices to follow the Beverloo law only when D exceeds a critical value (D_c) below which flow can be interrupted or stopped. This arrest of the flow of grains through an orifice called jamming is consequent upon the size of the orifice not being large enough compared to the size of the grain particles (Janda *et al.,* 2008). The dynamics of jamming is not the subject of this work. However, Garcimartin (2007), Mankoc *et al*. (2007) and Janda *et al.* (2008) posit that at D_c < 2.5 jamming may occur and affect the law of flow rate, thereby limiting the robousity of Beverloo's law for small D, for which Mankoc *et al.* (2007) had advanced an empirical mend. Also, they have stated that for D > 6, it is very unlikely that jamming will occur. With this in mind, a polynomials regression of the volume flow rate data obtained for African breadfruit seeds was done, which gave the following equations (equations 4 and 5).

$$Q_c = 0.017D^2 + 0.592D + 2.409 \qquad (R^2 = 1) \quad \ldots 4$$

$$Q_c = 0.016D^2 + 0.516D + 1.376 \qquad (R^2 = 1) \quad \ldots 5$$

From the above equations, it was found that jamming is unlikely to occur for African breadfruit seeds when D >17 for circular and D >16 for square orifices.

3.5 Effect of Orifice Diameter on Seed Velocity

With bulk density assured constant, the seed velocity calculated from the volume flow rate and the orifice area, was regressed against hydraulic and effective orifice diameters to get the following linear and power regression equations.

$$V_c = 0.017D_h + 0.059 \qquad (R^2 = 0.992) \quad \ldots 6$$

$$V_s = 0.016D_h + 0.034 \qquad (R^2 = 0.985) \quad \ldots 7$$

$$V_c = 0.051D_h^{0.645} \qquad (R^2 = 0.995) \quad \ldots 8$$

$$V_s = 0.037D_h^{0.700} \qquad (R^2 = 0.984) \quad \ldots 9$$

$$V_c = 0.017D_e + 0.077 \qquad (R^2 = 0.992) \quad \ldots 10$$

$$V_s = 0.016D_e + 0.050 \qquad (R^2 = 0.977) \quad \ldots 11$$

$$V_c = 0.070D_e^{0.532} \qquad (R^2 = 0.997) \quad \ldots 12$$

$$V_s = 0.053D_e^{0.568} \qquad (R^2 = 0.974) \quad \ldots 13$$

Chang *et al.* (1984) found the grain velocity of corn through both round and square orifices to vary almost linearly with orifice diameter. The linear equations of the flow rate of African breadfruit seeds with D_h and D_e above support that view with their high R^2 (0.977 to 0.992). However, their power regressions also had high R^2 (0.974 to 0.995). Further investigation showed that the polynomial regression had even higher R^2 as shown below.

$$V_c = 0.001D_h^2 + 0.034D_h + 0.007 \quad (R^2 = 0.998) \quad \ldots 14$$

$$V_s = 0.001D_h^{\ 2} - 0.004D_h + 0.089 \quad (R^2 = 0.994) \ldots 15$$

$$V_c = 0.001D_e^{\ 2} + 0.031D_e + 0.042 \quad (R^2 = 0.998) \ldots 16$$

$$V_s = 0.002D_e^{\ 2} - 0.004D_e + 0.095 \quad (R^2 = 0.990) \ldots 17$$

All the equations show that the seed velocity increases as the orifice size (hydraulic or effective) increases. Furthermore, since the flow rate of African breadfruit seeds in horizontal orifices has not been reported in Literature, the information postulated in this work becomes a necessary design tool in the appropriate design of hoppers and other material handling systems for the seeds.

4.0 Conclusions

i. The flow rate of African breadfruit seeds through horizontal orifices is higher for circular than square orifice by about 30%.

ii. The flow rate of African breadfruit seeds through horizontal orifices obeyed Beverloo law within the orifice sizes tested and gave exponents 2.529 and 2.568 for circular and square orifices respectively for D_e.

iii. The ratio $D = D_h/d$ is important in the jamming phenomenon of granular materials through orifices. For D e” 6 jamming is very unlikely and for African breadfruit seeds, D e” 16 for no jamming.

iv. Grain velocity increased almost linearly with orifice diameter, even though the power and polynomial regressions gave higher R^2.

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